

Origin of CP violation for leptogenesis in seesaw

Pei-Hong Gu*

Department of Physics and Astronomy, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China

We reveal the origin of the CP violation required by the leptogenesis in variously popular seesaw models. Especially we clarify that in a pure type-I/III seesaw with two fermion singlets/triplets, a combined type-I+III seesaw with one fermion singlet and one fermion triplet, or a combined type-I/III+II seesaw with one fermion singlet/triplet and one Higgs triplet, the CP violation for the leptogenesis can exactly come from the imaginary part of the neutrino mass matrix in a special basis where the Yukawa couplings involving one fermion singlet/triplet are allowed to get rid of any CP phases. We also generalize our findings as a very good approximation when these seesaw scenarios are extended by more fermion singlets/triplets and Higgs triplets while the leptogenesis is realized by the decays of the lightest fermion singlet/triplet.

PACS numbers: 98.80.Cq, 14.60.Pq

Introduction: The atmospheric, solar, accelerator and reactor neutrino experiments have established the phenomena of neutrino oscillations [1]. This requires a mixing among three flavors of massive neutrinos and hence a necessity for new physics beyond the standard model (SM). Meanwhile, the cosmological observations have indicated that the neutrino masses should be in a sub-eV range [1]. In order to naturally explain the smallness of the neutrino masses, we can resort to the famous seesaw mechanism [2–5]. The essential feature of the seesaw mechanism is that the neutrino masses can be highly suppressed by a small ratio of the electroweak scale over a newly high scale. Currently, the most popular seesaw models include the so-called type-I [2–5], type-II [6–10] and type-III [11] seesaw. The type-I/III seesaw is realized by introducing some fermion singlets/triplets with a heavy Majorana mass term as well as the Yukawa couplings to the SM lepton and Higgs doublets. As for the type-II seesaw, it contains some heavy Higgs triplets with the Yukawa couplings to the SM lepton doublets as well as the cubic couplings to the SM Higgs doublet.

Remarkably, these seesaw models can also accommodate a leptogenesis [12–21] mechanism to solve the puzzle of the cosmic matter-antimatter asymmetry, which is equivalent to a baryon asymmetry. In this seesaw and leptogenesis scenario, the neutrino mass and the baryon asymmetry can be simultaneously induced by certain interactions involving the newly heavy particles. However, such seesaw models contain many free parameters. This leads to a conventional wisdom that the corresponding leptogenesis cannot give a distinct relation between the baryon asymmetry and the neutrino mass matrix unless we do some assumptions on the texture of the relevant masses and couplings. For example, ones can expect a successful leptogenesis in the canonical type-I seesaw model even if the neutrino mass matrix does not contain any CP phases [22].

In this work we shall reveal that in a pure type-

I/III seesaw with two fermion singlets/triplets, a combined type-I+III seesaw with one fermion singlet and one fermion triplet, or a combined type-I/III+II seesaw with one fermion singlet/triplet and one Higgs triplet, the CP violation required by the leptogenesis exactly originates from the imaginary part of the neutrino mass matrix. This is because for a special basis, the Yukawa couplings involving one of the two fermion singlets/triplets or the unique Higgs triplet are always allowed to absorb all of the physical CP phases in the lepton sector. We shall also clarify that in the seesaw models with more fermion singlets/triplets and Higgs triplets, the imaginary part of the neutrino matrix approximately is the source of the CP violation for the leptogenesis by the decays of the lightest fermion singlet/triplet.

The type-I/II/III seesaw models: For simplicity, we do not write down the full SM Lagrangian. Instead, we only show the part of the lepton sector, i.e.

$$\mathcal{L}_{\text{SM}} \supset \sum_{\alpha} \left[i \bar{l}_{L\alpha} \not{D} l_{L\alpha} + i \bar{e}_{R\alpha} \not{D} e_{R\alpha} - y_{\alpha} \left(\bar{l}_{L\alpha} \tilde{\phi} e_{R\alpha} + \text{H.c.} \right) \right], \quad (1)$$

where ϕ , $l_{L\alpha}$ and $e_{R\alpha}$ ($\alpha = e, \mu, \tau$) respectively stand for the Higgs scalar, the left-handed leptons and the right-handed leptons, i.e.

$$\phi(1, 2, -\tfrac{1}{2}) = \begin{bmatrix} \phi^0 \\ \phi^- \end{bmatrix}, \quad l_{L\alpha}(1, 2, -\tfrac{1}{2}) = \begin{bmatrix} \nu_{L\alpha} \\ e_{L\alpha} \end{bmatrix}, \quad e_{R\alpha}(1, 1, -1). \quad (2)$$

Here and thereafter the brackets following the fields describe the transformations under the SM $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge groups. Note we have taken the Yukawa couplings in Eq. (1) to be real and diagonal without loss of generality and for convenience.

We then review the most general type-I/II/III seesaw

*Electronic address: peihong.gu@sjtu.edu.cn

[2–11],

$$\mathcal{L}_I = \sum_i \left[i\bar{N}_{Ri}\not{\partial}N_{Ri} - \frac{1}{2}M_{N_i}(\bar{N}_{Ri}N_{Ri}^c + \text{H.c.}) - \sum_\alpha (g_{\alpha i}\bar{l}_{L\alpha i}\phi N_{Ri} + \text{H.c.}) \right], \quad (3a)$$

$$\mathcal{L}_{II} = \sum_i \left\{ \text{Tr} \left[(D_\mu \Delta_i)^\dagger (D^\mu \Delta_i) \right] - M_{\Delta_i}^2 \text{Tr} (\Delta_i^\dagger \Delta_i) - \frac{1}{2}\mu_i (\phi^\dagger \Delta_i i\tau_2 \phi^* + \text{H.c.}) - (\text{quartic terms}) - \sum_{\alpha\beta} \left(\frac{1}{2}f_{\alpha\beta i}\bar{l}_{L\alpha}\Delta_i i\tau_2 l_{L\beta}^c + \text{H.c.} \right) \right\}, \quad (3b)$$

$$\mathcal{L}_{III} = \sum_i \left\{ i\text{Tr} (\bar{T}_{Li}\not{\partial}T_{Li}) - \frac{1}{2}M_{T_i} [\text{Tr} (\bar{T}_{Li}^c i\tau_2 T_{Li} i\tau_2) + \text{H.c.}] - \sum_\alpha \left(\sqrt{2}h_{\alpha i}\bar{l}_{L\alpha} i\tau_2 T_{Li}^c i\tau_2 \phi + \text{H.c.} \right) \right\}, \quad (3c)$$

where N_{Ri} , Δ_i and T_{Li} ($i = 1, \dots, n \geq 1$) respectively denote the fermion singlet(s), the Higgs triplet(s) and the fermion triplet(s), i.e.

$$N_{Ri}(1, 1, 0), \quad (4a)$$

$$\Delta_i(1, 3, -1) = \begin{bmatrix} \delta_i^-/\sqrt{2} & \delta_i^0 \\ \delta_i^{--} & -\delta_i^-/\sqrt{2} \end{bmatrix}, \quad (4b)$$

$$T_{Li}(1, 3, 0) = \begin{bmatrix} T_{Li}^0/\sqrt{2} & T_{Li}^+ \\ T_{Li}^- & -T_{Li}^0/\sqrt{2} \end{bmatrix}. \quad (4c)$$

In the above Lagrangians, the CP phases only exist in the Yukawa couplings involving the fermion singlet(s)/triplet(s) and the Higgs triplet(s). This can be always achieved by a proper phase rotation.

It is easy to see that in a type-I/III, type-I+III or type-I/III+II seesaw extension of the SM, the Yukawa couplings involving one fermion singlet/triplet can be further chosen to be real. In other words, all of the CP

phases in the lepton sector can be included in the Yukawa couplings of the other fermion singlet(s)/triplet(s) to the lepton and Higgs doublets, and/or the Yukawa couplings of the Higgs triplet(s) to the lepton doublets. For the following demonstration, we conveniently assign

$$g_{\alpha 1} \equiv g_{\alpha 1}^* \quad \text{or} \quad h_{\alpha 1} \equiv h_{\alpha 1}^*. \quad (5)$$

Actually, the above assignment can be understood by the phase rotation as below,

$$X g \rightarrow g \quad \text{or} \quad X h \rightarrow h$$

$$\text{with } X = \text{diag}\{e^{i\beta_1}, e^{i\beta_2}, e^{i\beta_3}\}. \quad (6)$$

The neutrino mass matrix and its CP phases: When the Higgs scalar ϕ develops its VEV $\langle \phi \rangle = \langle \phi^0 \rangle = v \simeq 174 \text{ GeV}$ to spontaneously break the electroweak symmetry, the left-handed neutrinos ν_L can acquire a tiny Majorana mass term by integrating out the heavy fermion singlet(s)/triplet(s) and/or Higgs triplet(s), i.e.

$$\mathcal{L} \supset -\frac{1}{2}\bar{\nu}_L m_\nu \nu_L^c + \text{H.c.} \quad \text{with}$$

$$m_\nu = m_\nu^I + m_\nu^{II} + m_\nu^{III} = X U \hat{m} U^T X^T. \quad (7)$$

Here the mass matrices $m_\nu^{I/II/III}$ are the type-I/II/III seesaw [2–11],

$$(m_\nu^I)_{\alpha\beta} = -\sum_i g_{\alpha i} g_{\beta i} \frac{v^2}{M_{N_i}}, \quad (8a)$$

$$(m_\nu^{II})_{\alpha\beta} = -\sum_i f_{\alpha\beta i} \frac{\mu_i v^2}{2M_{\Delta_i}^2}, \quad (8b)$$

$$(m_\nu^{III})_{\alpha\beta} = -\sum_i h_{\alpha i} h_{\beta i} \frac{v^2}{M_{T_i}}, \quad (8c)$$

the diagonal matrix \hat{m} gives three neutrino mass eigenvalues,

$$\hat{m} = \text{diag}\{m_1, m_2, m_3\}, \quad (9)$$

while the PMNS matrix U determines the mixing among three neutrino flavors [1],

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \times \text{diag}\{e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1\}. \quad (10)$$

Clearly the neutrino mass matrix m_ν is allowed to con-

tain three physical CP phases: two Majorana phases $\alpha_{1,2}$

and one Dirac phase δ . The physical CP phases $\alpha_{1,2}$ and δ as well as the unphysical CP phases $\beta_{1,2,3}$ can appear if and only if there are some complex Yukawa couplings in the seesaw formula (8). By inserting the assignment (5) into the seesaw formula (8), we conclude in the pure type-I/III seesaw, the combined type-I+III seesaw or the combined type-I/III+II seesaw, one fermion singlet/triplet will never contribute to the imaginary part of the neutrino mass matrix, i.e.

- in the type-I seesaw,

$$\text{Im} \left[(m_\nu)_{\alpha\beta} \right] = -\text{Im} \left(\sum_{i \neq 1} g_{\alpha i} g_{\beta i} \frac{v^2}{M_{N_i}} \right), \quad (11)$$

- in the type-III seesaw,

$$\text{Im} \left[(m_\nu)_{\alpha\beta} \right] = -\text{Im} \left(\sum_{i \neq 1} h_{\alpha i} h_{\beta i} \frac{v^2}{M_{T_i}} \right), \quad (12)$$

- in the type-I+III seesaw,

$$\begin{aligned} \text{Im} \left[(m_\nu)_{\alpha\beta} \right] &= -\text{Im} \left(\sum_{i \neq 1} g_{\alpha i} g_{\beta i} \frac{v^2}{M_{N_i}} + \sum_j h_{\alpha j} h_{\beta j} \frac{v^2}{M_{T_j}} \right), \\ \text{or } \text{Im} \left[(m_\nu)_{\alpha\beta} \right] &= -\text{Im} \left(\sum_i g_{\alpha i} g_{\beta i} \frac{v^2}{M_{N_i}} + \sum_{j \neq 1} h_{\alpha j} h_{\beta j} \frac{v^2}{M_{T_j}} \right), \end{aligned} \quad (13)$$

- in the type-I+II seesaw,

$$\begin{aligned} \text{Im} \left[(m_\nu)_{\alpha\beta} \right] &= -\text{Im} \left(\sum_{i \neq 1} g_{\alpha i} g_{\beta i} \frac{v^2}{M_{N_i}} + \sum_j f_{\alpha\beta j} \frac{\mu_j v^2}{2M_{\Delta_j}^2} \right), \end{aligned} \quad (14)$$

- in the type-III+II seesaw,

$$\begin{aligned} \text{Im} \left[(m_\nu)_{\alpha\beta} \right] &= -\text{Im} \left(\sum_{i \neq 1} h_{\alpha i} h_{\beta i} \frac{v^2}{M_{T_i}} + \sum_j f_{\alpha\beta j} \frac{\mu_j v^2}{2M_{\Delta_j}^2} \right). \end{aligned} \quad (15)$$

The CP violation for leptogenesis: Either the fermion singlet(s)/triplet(s) or the Higgs triplet(s) or both can decay to generate a lepton asymmetry as long as the CP is not conserved. This lepton asymmetry then can partially get converted to a baryon asymmetry through the sphaleron processes [23]. Specifically, the final baryon asymmetry can be described by [24]

$$\eta_B = c_{\text{sph}} \frac{\sum_i \kappa_{N_i} \varepsilon_{N_i} + \sum_j \kappa_{\Delta_j} \varepsilon_{\Delta_j} r_{\Delta_j} + \sum_k \kappa_{T_k} \varepsilon_{T_k} r_{T_k}}{g_*}. \quad (16)$$

Here $c_{\text{sph}} = -\frac{28}{79}$ [25] is the sphaleron lepton-to-baryon coefficient, $g_* = 106.75$ [24] is the relativistic degrees of freedom during the leptogenesis epoch, $\kappa_{N_i/\Delta_i/T_i} \lesssim 1$ denote the washout factors and their exact numbers are solved by the related Boltzmann equations, $r_{\Delta_i/T_i} = 3$ appear for the triplets, while $\varepsilon_{N_i/\Delta_i/T_i}$ are the CP asymmetries in the decays of the fermion singlet $N_i = N_{Ri} + (N_{Ri})^c = N_i^c$, the Higgs triplet pair (Δ_i, Δ_i^*) and the fermion triplet $T_i = (T_i^-, T_i^0, T_i^+)$ with $T_i^0 = T_{Li}^0 + (T_{Li}^0)^c = (T_{Li}^0)^c$ and $T_i^\pm = T_{Li}^\pm + (T_{Li}^\mp)^c = (T_{Li}^\mp)^c$. The CP asymmetries $\varepsilon_{N_i/\Delta_i/T_i}$ well characterize the CP violation required by the leptogenesis and they are evaluated at one-loop level [12–21],

$$\varepsilon_{N_i} = \frac{1}{8\pi} \frac{\sum_{\alpha\beta} \text{Im} \left\{ g_{\alpha i}^* g_{\beta i}^* \left[\sum_{j \neq i} g_{\alpha j} g_{\beta j} I_{N_i}^{N_j} + \sum_k f_{\alpha\beta k} \frac{\mu_k}{2M_{N_i}} I_{N_i}^{\Delta_k} + \sum_l h_{\alpha l} h_{\beta l} I_{N_i}^{T_l} \right] \right\}}{\sum_{\alpha} g_{\alpha i}^* g_{\alpha i}}, \quad (17)$$

$$\varepsilon_{\Delta_i} = \frac{1}{8\pi} \frac{\sum_{\alpha\beta} \text{Im} \left\{ f_{\alpha\beta i}^* \frac{\mu_i}{M_{\Delta_i}} \left[g_{\alpha j} g_{\beta j} \sum_j I_{\Delta_i}^{N_j} + \sum_{k \neq i} f_{\alpha\beta k} \frac{\mu_k}{M_{\Delta_i}} I_{\Delta_i}^{\Delta_k} + \sum_l h_{\alpha l} h_{\beta l} I_{\Delta_i}^{T_l} \right] \right\}}{\sum_{\alpha\beta} f_{\alpha\beta i}^* f_{\alpha\beta i} + \frac{\mu_i^2}{M_{\Delta_i}^2}}, \quad (18)$$

$$\varepsilon_{T_i} = \frac{1}{8\pi} \frac{\sum_{\alpha\beta} \text{Im} \left\{ h_{\alpha i}^* h_{\beta i}^* \left[g_{\alpha j} g_{\beta j} \sum_j I_{T_i}^{N_j} + \sum_k f_{\alpha\beta k} \frac{\mu_k}{2M_{T_i}} I_{T_i}^{\Delta_k} + \sum_{l \neq i} h_{\alpha l} h_{\beta l} I_{T_i}^{T_l} \right] \right\}}{\sum_{\alpha} h_{\alpha i}^* h_{\alpha i}}, \quad (19)$$

where the functions $I_{F_i}^{F_j}$, $I_{F_i}^{\Delta_j}$, $I_{\Delta_i}^{\Delta_j}$ and $I_{\Delta_i}^{F_j}$ ($F_i = N_i/T_i$) are calculated by

$$\begin{aligned}
I_{F_i}^{F_j} &\equiv I_{F_i}^{F_j} \left[\frac{M_{F_i}^2}{M_{F_j}^2} \right] \quad \text{with} \\
I_{F_i}^{F_j}[x] &= \frac{\sqrt{x}}{1-x} + \frac{1}{\sqrt{x}} \left[-1 + \left(1 + \frac{1}{x} \right) \ln(1+x) \right], \\
I_{F_i}^{\Delta_j} &\equiv I_{F_i}^{\Delta_j} \left[\frac{M_{F_i}^2}{M_{\Delta_j}^2} \right] \quad \text{with} \\
I_{F_i}^{\Delta_j}[x] &= 3 \left[1 - \frac{1}{x} \ln(1+x) \right], \\
I_{\Delta_i}^{\Delta_j} &\equiv I_{\Delta_i}^{\Delta_j} \left[\frac{M_{\Delta_i}^2}{M_{\Delta_j}^2} \right] \quad \text{with} \quad I_{\Delta_i}^{\Delta_j}[x] = \frac{2x}{1-x}, \\
I_{\Delta_i}^{F_j} &\equiv I_{\Delta_i}^{F_j} \left[\frac{M_{\Delta_i}^2}{M_{F_j}^2} \right] \quad \text{with} \quad I_{\Delta_i}^{F_j}[x] = \frac{2}{\sqrt{x}} \ln(1+x). \quad (20)
\end{aligned}$$

We find the CP violation $\varepsilon_{N_i/\Delta_i/T_i}$ can have an exact or approximate dependence on the imaginary part of the neutrino mass matrix in some cases. Actually we read

- in the type-I seesaw with two fermion singlets,

$$\varepsilon_{N_1} = \frac{1}{8\pi} \frac{\sum_{\alpha\beta} g_{\alpha 1} g_{\beta 1} \text{Im}[(m_\nu)_{\alpha\beta}] M_{N_2} I_{N_1}^{N_2}}{v^2 \sum_{\alpha} g_{\alpha 1}^2}, \quad (21a)$$

$$\varepsilon_{N_2} = -\frac{1}{8\pi} \frac{\sum_{\alpha\beta} g_{\alpha 1} g_{\beta 1} \text{Im}[(m_\nu)_{\alpha\beta}] M_{N_1} I_{N_2}^{N_1}}{v^2 \sum_{\alpha} g_{\alpha 2}^2 g_{\alpha 2}}, \quad (21b)$$

- in the type-III seesaw with two fermion triplets,

$$\varepsilon_{T_1} = \frac{1}{8\pi} \frac{\sum_{\alpha\beta} h_{\alpha 1} h_{\beta 1} \text{Im}[(m_\nu)_{\alpha\beta}] M_{T_2} I_{T_1}^{T_2}}{\sum_{\alpha} h_{\alpha 1}^2}, \quad (22a)$$

$$\varepsilon_{T_2} = -\frac{1}{8\pi} \frac{\sum_{\alpha\beta} h_{\alpha 1} h_{\beta 1} \text{Im}[(m_\nu)_{\alpha\beta}] M_{T_1} I_{T_2}^{T_1}}{\sum_{\alpha} h_{\alpha 2}^* h_{\alpha 2}}, \quad (22b)$$

- in the type-I+III seesaw with one fermion singlet and one fermion triplet,

$$\varepsilon_{N_1} = \frac{1}{8\pi} \frac{\sum_{\alpha\beta} g_{\alpha 1} g_{\beta 1} \text{Im}[(m_\nu)_{\alpha\beta}] M_{T_1} I_{N_1}^{T_1}}{v^2 \sum_{\alpha} g_{\alpha 1}^2}, \quad (23a)$$

$$\varepsilon_{T_1} = -\frac{1}{8\pi} \frac{\sum_{\alpha\beta} g_{\alpha 1} g_{\beta 1} \text{Im}[(m_\nu)_{\alpha\beta}] M_{N_1} I_{T_1}^{N_1}}{v^2 \sum_{\alpha} h_{\alpha 1}^* h_{\alpha 1}}, \quad (23b)$$

- in the type-I+II seesaw with one fermion singlet

and one Higgs triplet,

$$\varepsilon_{N_1} = \frac{1}{8\pi} \frac{\sum_{\alpha\beta} g_{\alpha 1} g_{\beta 1} \text{Im}[(m_\nu)_{\alpha\beta}] M_{\Delta_1} I_{N_1}^{\Delta_1}}{v^2 \sum_{\alpha} g_{\alpha 1}^2}, \quad (24a)$$

$$\varepsilon_{\Delta_1} = -\frac{1}{8\pi} \frac{\sum_{\alpha\beta} g_{\alpha 1} g_{\beta 1} \text{Im}[(m_\nu)_{\alpha\beta}] M_{N_1} I_{\Delta_1}^{N_1}}{v^2 \left(\sum_{\alpha\beta} f_{\alpha\beta 1}^* f_{\alpha\beta 1} + \frac{\mu_1^2}{M_{\Delta_1}^2} \right)}, \quad (24b)$$

- in the type-III+II seesaw with one fermion triplet and one Higgs triplet,

$$\varepsilon_{T_1} = \frac{1}{8\pi} \frac{\sum_{\alpha\beta} h_{\alpha 1} h_{\beta 1} \text{Im}[(m_\nu)_{\alpha\beta}] M_{\Delta_1} I_{T_1}^{\Delta_1}}{v^2 \sum_{\alpha} h_{\alpha 1}^2}, \quad (25a)$$

$$\varepsilon_{\Delta_1} = -\frac{1}{8\pi} \frac{\sum_{\alpha\beta} h_{\alpha 1} h_{\beta 1} \text{Im}[(m_\nu)_{\alpha\beta}] M_{T_1} I_{\Delta_1}^{T_1}}{v^2 \left(\sum_{\alpha\beta} f_{\alpha\beta 1}^* f_{\alpha\beta 1} + \frac{\mu_1^2}{M_{\Delta_1}^2} \right)}. \quad (25b)$$

When the above special seesaw models are extended by more fermion singlet(s)/triplet(s) and Higgs triplet(s), we can expect a leptogenesis by the decays of the lightest fermion singlet/triplet. In this case, we can denote the lightest fermion singlet/triplet by N_1/T_1 and then consider the assignment (5) in Eqs. (17) and (19). The CP violation then can be simplified as

$$\begin{aligned}
\varepsilon_{N_1} &= \frac{3}{16\pi} \frac{\sum_{\alpha\beta} \left\{ g_{\alpha 1} g_{\beta 1} \text{Im}[(m_\nu)_{\alpha\beta}] \right\} M_{N_1}}{v^2 \sum_{\alpha} g_{\alpha 1}^2} \quad \text{or} \\
\varepsilon_{T_1} &= \frac{3}{16\pi} \frac{\sum_{\alpha\beta} \left\{ h_{\alpha 1} h_{\beta 1} \text{Im}[(m_\nu)_{\alpha\beta}] \right\} M_{T_1}}{v^2 \sum_{\alpha} h_{\alpha 1}^2}, \quad (26)
\end{aligned}$$

which is easy to give us an upper bound [26, 27].

Ones may be interested in the so-called Davidson-Ibarra parametrization [22], under which the Yukawa couplings g/h in the pure type-I/III seesaw are determined by

$$\begin{aligned}
g_{\alpha i} &= i \sum_j U_{\alpha j} \sqrt{m_j} O_{ji} \sqrt{M_{N_i}}/v \quad \text{or} \\
h_{\alpha i} &= i \sum_j U_{\alpha j} \sqrt{m_j} O_{ji} \sqrt{M_{T_i}}/v, \quad (27)
\end{aligned}$$

with O being an arbitrary complex orthogonal matrix. Ones hence conclude that in the presence of the complex orthogonal matrix O , the Yukawa couplings g/h can be complex even if the PMNS matrix U does not contain any CP phases. The CP asymmetry (26) then can be

irrelevant to the PMNS matrix, i.e.

$$\begin{aligned}\varepsilon_{N_1} &= -\frac{3}{16\pi} \frac{\text{Im} \left\{ \sum_{j \neq 1} \left(\sum_k O_{k1}^* O_{kj} m_k \right)^2 \right\} M_{N_1}}{v^2 \sum_k |O_{k1}|^2 m_k} \quad \text{or} \\ \varepsilon_{T_1} &= -\frac{3}{16\pi} \frac{\text{Im} \left\{ \sum_{j \neq 1} \left(\sum_k O_{k1}^* O_{kj} m_k \right)^2 \right\} M_{T_1}}{v^2 \sum_k |O_{k1}|^2 m_k}. \quad (28)\end{aligned}$$

Under our assignment (5), the CP asymmetry (26) depends on a complex diagonal matrix X besides the PMNS matrix U , see Eqs. (6) and (7). Clearly, our X matrix is very simple, compared with the O matrix.

Conclusion: In this work we have revealed the origin of the CP violation for the leptogenesis in the most popular seesaw models. Specifically, we find that in a pure type-I/III seesaw with two fermion singlets/triplets, a combined type-I+III seesaw with one fermion singlet and one fermion triplet, or a combined type-I/III+II seesaw with one fermion singlet/triplet and one Higgs triplet, the Yukawa couplings involving one of the two fermion

singlets/triplets or the unique Higgs triplet are always allowed to absorb all of the physical CP phases in the lepton sector. In this basis, the CP violation required by the leptogenesis should exactly come from the imaginary part of the neutrino matrix. We also consider a generalization in the case that these seesaw scenarios are extended by more fermion singlets/triplets and Higgs triplets while the leptogenesis is realized by the decays of the lightest fermion singlet/triplet. This generalization is a very good approximation and is reliable even in the radiative type-I/III and type-I+III seesaw [28, 29] where an inert Higgs doublet, rather than the SM Higgs doublet, is responsible for the Yukawa couplings of the fermion singlet(s)/triplet(s) to the SM lepton doublets.

Acknowledgement: This work was supported by the Recruitment Program for Young Professionals under Grant No. 15Z127060004, the Shanghai Jiao Tong University under Grant No. WF220407201, the Shanghai Laboratory for Particle Physics and Cosmology under Grant No. 11DZ2260700 and the Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education.

-
- [1] C. Patrignani *et al.*, (Particle Data Group Collaboration), Chin. Phys. C **40**, 1000001 (2016).
 - [2] P. Minkowski, Phys. Lett. B **67**, 421 (1977).
 - [3] T. Yanagida, *Proceedings of the Workshop on Unified Theory and the Baryon Number of the Universe*, ed. O. Sawada and A. Sugamoto (Tsukuba 1979).
 - [4] M. Gell-Mann, P. Ramond, and R. Slansky, *Supergravity*, ed. F. van Nieuwenhuizen and D. Freedman (North Holland 1979).
 - [5] R.N. Mohapatra and G. Senjanović, Phys. Rev. Lett. **44**, 912 (1980).
 - [6] M. Magg and C. Wetterich, Phys. Lett. B **94**, 61 (1980).
 - [7] J. Schechter and J.W.F. Valle, Phys. Rev. D **22**, 2227 (1980).
 - [8] T.P. Cheng and L.F. Li, Phys. Rev. D **22**, 2860 (1980).
 - [9] G. Lazarides, Q. Shafi, and C. Wetterich, Nucl. Phys. B **181**, 287 (1981).
 - [10] R.N. Mohapatra and G. Senjanović, Phys. Rev. D **23**, 165 (1981).
 - [11] R. Foot, H. Lew, X.G. He, and G.C. Joshi, Z. Phys. C **44**, 441 (1989).
 - [12] M. Fukugita and T. Yanagida, Phys. Lett. B **174**, 45 (1986).
 - [13] P. Langacker, R.D. Peccei, and T. Yanagida, Mod. Phys. Lett. A **1**, 541 (1986).
 - [14] M.A. Luty, Phys. Rev. D **45**, 455 (1992).
 - [15] R.N. Mohapatra and X. Zhang, Phys. Rev. D **46**, 5331 (1992).
 - [16] M. Flanz, E.A. Paschos, and U. Sarkar, Phys. Lett. B **345**, 248 (1995).
 - [17] L. Covi, E. Roulet, and F. Vissani, Phys. Lett. B **384**, 169 (1996).
 - [18] A. Pilaftsis, Phys. Rev. D **56**, 5431 (1997).
 - [19] E. Ma and U. Sarkar, Phys. Rev. Lett. **80**, 5716 (1998).
 - [20] T. Hambye and G. Senjanović, Phys. Lett. B **582**, 73 (2004).
 - [21] S. Antusch and S.F. King, Phys. Lett. B **597**, 199 (2004).
 - [22] S. Davidson and A. Ibarra, Nucl. Phys. B **618**, 171 (2001).
 - [23] V.A. Kuzmin, V.A. Rubakov, and M.E. Shaposhnikov, Phys. Lett. B **155**, 36 (1985).
 - [24] E.W. Kolb and M.S. Turner, *The Early Universe*, Addison-Wesley, 1990.
 - [25] J.A. Harvey and M.S. Turner, Phys. Rev. D **42**, 3344 (1990).
 - [26] S. Davidson and A. Ibarra, Phys. Lett. B **535**, 25 (2002).
 - [27] W. Buchmüller, P. Di Bari, and M. Plümacher, Nucl. Phys. B **665**, 445 (2003).
 - [28] E. Ma, Phys. Rev. D **73**, 077301 (2006).
 - [29] J. Kubo, E. Ma, and D. Suematsu, Phys. Lett. B **642**, 18 (2006).